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Fast reactors and nuclear nonproliferation problem

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Abstract

The growing number of countries wishing to use nuclear energy, and the expansion in the geography of NPPs entails the risk of nuclear weapons proliferation, given that political leaders in some countries may want to purchase or develop sensitive nuclear technologies. A certain risk of proliferation through nuclear power technologies and materials cannot be excluded altogether. In the nuclear fuel cycle there are large inventories of nuclear materials, including fissile materials, (many hundreds and thousands of tons). The problem of spent nuclear fuel with plutonium in it, especially for novice countries and countries with small nuclear power program, also increases the risk of proliferation, including the growing risk of actions on the part of subnational or terrorist organizations because of the proliferation of nuclear technologies and materials as respective protection measures are insufficient in these countries.

In the event of thermal reactors, uranium enrichment is indispensable to production of fuel. Long-term storage of SNF from thermal reactors in an open fuel cycle, which is a common practice nowadays, entails an increased risk of proliferation due to the weakening of the radiation barrier over time and the potentiality of unauthorized removal of fuel by the proliferator state and its theft by criminals and terrorists.

Fast-neutron reactors started up and operating on plutonium fuel do not require uranium enrichment. There is no long-term storage of SNF in the closed fuel cycles of fast reactors. Gradual replacement of thermal reactors by fast reactors, due to natural uranium being in short supply, creates prerequisites for phasing out uranium enrichment. However, countries having small nuclear power programs and, therefore, a limited number of nuclear units will use thermal reactors still for a long time, which will require uranium enrichment.

Creation of nuclear weapons based on energy-grade plutonium using a simpler “gun-type” design is practically impossible because of a high neutron background inherent in this kind of plutonium. However, this does not exclude the potentiality of terrorist attempts to fabricate a primitive nuclear explosive device.

Both sensitive technologies (uranium enrichment and SNF processing with separation of plutonium) will be used to start up fast reactors on uranium fuel with the subsequent transition to plutonium fuel. In this case, plutonium with a small content of higher isotopes will be bred not only in the blanket, but also in the reactor core in much greater quantities.

The paper considers various technological and institutional approaches to solving the problem of fast reactor blankets in terms of ensuring a strong proliferation resistance.

Keywords: Nuclear fuel cycle; Nonproliferation of nuclear weapons; Fissile materials; Plutonium; Enriched uranium; Fast reactors; Thermal reactors.

Introduction

In more than 50 years of its existence, international nuclear power has come a long way of evolution and has expanded worldwide. However, the underlying nuclear technologies, though improved over time, remain the legacy of the military and require careful attention to nonproliferation issues.

The evolution of the nuclear power system and infrastructure, with a great deal of fissile materials being still in the system, creates motivation and prerequisites for the peaceful material of the nuclear fuel cycle (NFC) to be used for building nuclear weapons (NW) or stolen for making nuclear explosive devices (NED).

The 1978 decision by the administration of the US President J. Carter to give up the processing of SNF and wind up the fast breeder reactor program because of the alleged risk of nuclear

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proliferation from the use of plutonium in fast-neutron reactors has been harmful to the progress of this technology both in the USA in and some other countries. Besides (primarily owing to the USA), there has been a negative attitude formed in the world towards fast reactors and their NFC as being most dangerous in terms of nuclear proliferation. At the same time, the decision by Carter's administration ignored the danger of proliferation from the uranium enrichment technology. Apparently, the reason for this was the fact that the development of the centrifuge enrichment technology in the USA at the time was not successful, and the US-designed centrifuges as such were rather cumbersome and up to 12 m high. And the gas-diffusion technology demonstrated at the time was introduced at large-size facilities with much electricity and water consumed. For example, a plant in Paducah, Kentucky, of the capacity ∼7 million SWR/started up in 1954, consumed 22 billion kW per year, and its cooling water consumption exceeded several-fold the water consumption by New York's municipal water supply system [1].

It was only natural to imagine then that such facility could not be 'hidden' for the covert production of enriched uranium. The success of the centrifuge technology, especially in the USSR, small dimensions of centrifuges (no more than one meter high), and a several-fold decrease in the consumption of electricity and water have brought about a certain risk of high-enriched uranium to be covertly produced.

Problem definition

Existing definitions of proliferation resistance

In one of its earliest definitions, the notion "proliferation" was used in a publication by Silvennoinen and Vira, US scientists, in 1986: "The development of the material and technical resources required for the production of nuclear explosives in countries that now do not have such a capability" [2].

Later on, the term "nonproliferation" was given a more specific meaning as applied to nuclear power systems. Thus, in the INPRO international project, "nonproliferation" or "proliferation resistance" is defined as follows: "Proliferation Resistance is defined as that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States intent on acquiring nuclear weapons or other nuclear explosive devices." [3].

The definition of "proliferation resistance" in the Generation IV International Forum is practically the same as in the INPRO project: "Proliferation resistance is such characteristic of a nuclear power system that impedes (prevents) the diversion or undeclared production of nuclear material or undeclared use of the technology by the holder state so that to possess nuclear weapons or other nuclear explosive devices". This definition is used in the Generation IV International Forum together with the notion of "physical protection": "Physical protection is such characteristic of a nuclear power system that impedes (prevents) the theft of materials fit for nuclear explosive of radiation dispersing devices, as well as other acts of sabotage against plants or transport by subnational organizations and adversaries other than belonging to the holder state" [4].

As can be seen from the above definitions, "nonproliferation" in both international projects is concerned with proliferation at the state level. And in the Generation IV International Forum, emphasis is also placed on physical protection for prevention of potential nuclear terrorist acts by subnational organizations and groupings other than belonging to the holder state.

Potential ways for proliferation through NFC

Nuclear power is not the only way to creation of nuclear weapons, at the same time, it may be easier for threshold states to build nuclear weapons covertly, under the disguise of nuclear power.

The NFC's initial fissile materials may be processed into materials to be suitable for use in weapons at the state level or stolen by subnational or criminal groups.

The following steps can be made at the state level towards the creation of nuclear weapons:

- use of nuclear technologies, plants or nuclear power materials for a covert military program;
- use of the expertise and experience of nuclear experts for a parallel covert military program;
- withdrawal from the NPT and direct use of the NFC technologies, plants and materials for military purposes.

At the subnational (terrorist) level, nuclear materials can be stolen from the NFC facilities for making a primitive NED or a "dirty bomb".

Potential increase in proliferation risk in modern conditions

Prior to the accident at Fukushima-Daiichi nuclear plant in Japan in March 2011, about 40 countries declared their intent to use atomic energy for peaceful purposes. The number of such countries remains large despite the accident in Japan, and, as predicted, some 15 to 20 countries will have the first nuclear power units in their territories by 2030 [5].

The growth in the number of the countries wishing to use nuclear energy and the expansion in the NPP deployment geography may lead to an increase in the proliferation risk because political leaders in some countries may want to buy or develop sensitive nuclear technologies.

Recently, in connection with the intensive activities undertaken by Iran in the direction of uranium enrichment, some countries become suspicious that Iran is seeking to develop nuclear weapons. While neglecting the question of how justified are such suspicions, it should be noted that some of Iran's neighbor countries have also concerns in this respect. In particular, *The Guardian*, a British newspaper, said on 30 June 2011 that Saudi Arabia had warned the NATO that it would seek to get nuclear weapon if it was created by Iran [6]. One may suggest in this connection that the creation of nuclear weapons by Iran may trigger a "chain reaction" in the neighboring country for the purchase(creation) of such weapons and, as the result, the appearance of the whole range of threshold countries is concerned.

De-facto, the appearance of nuclear weapons in India and Pakistan, tests of nuclear devices in North Korea and the disability of the international community to prevent these actions serve an example for other unstable regimes as far as the possession of nuclear weapons is concerned. The Nuclear Nonproliferation Treaty (NPT) seems to require to be modified to a great extent so that countries would find it unprofitable, both politically and economically, to buy or develop nuclear weapons. An international mechanism of compensations shall be developed for the refusal to develop or possess nuclear weapons.

For the novice states which are embarking on the way to using atomic energy, an important dilemma will be the choice whether to create their own nuclear power infrastructure, in particular, for the SNF handling, or to use services from countries with such developed infrastructure. The problem with SNF and the plutonium in it, especially for novice countries and the countries with small nuclear power programs, also leads to an increased risk of proliferation, including a growing risk of actions on the part of subnational or terrorist organizations because of the proliferation of nuclear technologies and materials as protection measures are insufficient in these countries.

Fissile materials of nuclear power

A risk of proliferation through nuclear technologies or materials cannot be excluded altogether. A nuclear cycle contains huge inventories of nuclear materials amounting to many hundreds and thousands of tons, including fissile materials. Dozens of kg or less is enough to make a nuclear bomb.

Though uranium and plutonium can be used for production of nuclear explosives, they differ basically in terms of the proliferation risk reduction. The difference consists in that high-enriched uranium may be "mechanically" diluted by low-enriched or natural uranium as the result of which it loses its capacity for a chain fission reaction. It is possible to restore this capacity in diluted uranium only using technology and equipment for its enrichment which are also limitedly accessible. And it is much easier to separate plutonium from other elements it may be mixed with, because this will require only chemical treatment.

On the other hand, a neutronic comparison of uranium and plutonium shows that, unlike uranium, plutonium has certain inherent security properties which may make NED creation more difficult. Such properties include natural radiation background, heat release and radioactivity. The manifestation of these properties naturally depends on the content of certain isotopes in plutonium. Enriched uranium also has such properties but they are weaker by an order of magnitude than in plutonium, so they cannot have any notable effect on the NED creation.

It also seems obvious that, unlike terrorist groups, the proliferator is interested in building a "good" nuclear weapon, that is, a weapon of a great destructive power. The creation of such a weapon from uranium requires a technology for its enrichment (or for production of uranium-233 from thorium) and a relatively simple "gun-type" design for NED. In this connection, the problem of ensuring nuclear weapon nonproliferation through a uranium enrichment technology becomes especially acute.

For using plutonium, it is enough to have plutonium of a particular grade and rather a complicated explosive design of the implosion type. However, it cannot be definitely denied that energy-grade plutonium is not the target for the proliferator state as well.

Peculiarities of fast and thermal reactors in the field of nonproliferation

At the present time, two technologies developed in the early period of the nuclear weapon creation – uranium enrichment and processing of irradiated fuel with separation of plutonium – seem to be the most sensitive nuclear power technologies possessed by few countries. It is only reasonable to suggest that an increase in the number of the countries possessing these technologies leads to a greater risk of nuclear proliferation.

In the event of thermal reactors, uranium enrichment technology is indispensable to production of fuel. Long-term storage of SNF from thermal reactors in an open nuclear cycle, which is a common practice nowadays, entails a growing risk of proliferation due to the weakening of the radiation barrier over time, and the potentiality of unauthorized removal of this fuel by the proliferator state or its theft by a terrorist group.

Fast reactors started up and operating on mixed uranium-plutonium fuel do not require a uranium enrichment technology. There is no long-term storage of SNF in a closed fuel cycle. Given the fact that this fuel is cooled for a comparatively short time after it is withdrawn from the reactor, the fuel will be processed. The fact that thermal reactors are gradually replaced by fast reactors, due to natural uranium being in shorty supply, creates grounds for uranium enrichment to be phased out. Nevertheless, countries with small nuclear power programs and, consequently, a small number of units will use thermal reactors still for a long time, which will require a uranium enrichment technology.

Nuclear weapons with a simpler "gun-type" design cannot be practically created based on energy-grade plutonium because this plutonium has a high radiation background. This does not however rule out altogether certain attempts of making a primitive NED by a group of terrorists.

An implosion-type design requires a mature technology, tests of certain NED components (e.g. explosive lenses)and testing of the serviceability of the device as such. It may be suggested that this can be done only by the proliferator state and only provided that the country possesses a technologically and industrially developed infrastructure.

Startup and operation of fast reactors on plutonium

It was early as the start of the nuclear power evolution that Fermi came out with an idea that the first fast reactors will be started on plutonium to be produced in thermal reactors for peaceful nuclear applications (energy-grade plutonium). Energy-grade plutonium has a high content of even isotopes giving a pronounced radiation background. High content of plutonium-238 leads to rather a high heat release, while decay of plutonium-241 gives rise to radiological problems.

After irradiation in a fast reactor, the fuel manufactured based on energy-grade plutonium will contain plutonium with the

Table 1
Changes in the plutonium isotope composition in a fast reactor.

Isotope composition of plutonium, % Pu-239/Pu-240/Pu-241/Pu-242		Equilibrium composition of plutonium, % Pu-239/Pu-240/Pu-241/Pu-242
Loaded into reactor	Unloaded from reactor	
100/0/0/0	89.2/10.5/0.3/0.02	59.3/31.4/5.7/3.6
60/25/10.9/4.1	58.7/28.4/8.1/4.8	49.1/35.9/7.9/7.1
55/20.8/17.8/5.9	57.5/24.3/11.1/7.1	53.2/33.0/7.3/6.5
43.2/38.8/10.3/7.7	43.8/38.8/9.2/8.2	45.5/37.9/7.9/8.7
41/40/8/11	41/40/8/11	41/40/8/11

isotope composition having no major differences from that in the initial plutonium in fresh fuel.

Generally speaking, the isotope composition of the plutonium unloaded from reactors of different types and coming into the external fuel cycle of a nuclear power system will change over time to reach, in the long run, a certain limiting equilibrium composition. The equilibrium composition of plutonium in the system will be determined from the quantitative ratio of fast and thermal reactors in the system, as well as from the produced plutonium mixing conditions.

The results of the calculations conducted on a BN-800 fast reactor model are presented in Table 1.

Therefore, thermal reactors started up and operating with plutonium fuel in the reactor core generate plutonium of rather a poor grade in terms of the use in nuclear weapons.

It is quite different with fast reactors which have external breeding areas, called blankets. The blankets of thermal reactors are known to accumulate plutonium with an isotope composition close to that of weapon-grade plutonium [7]. This poses a certain risk of proliferation since such plutonium, having a small content of higher isotopes and plutonium-238, may be used in weapons actually with no prior processing.

Apart from institutional measures, this problem can be solved through the following:

– joint handling and processing of spent FAs from the reactor core and the blanket spent assemblies;
– exclusion of pure plutonium separation in the processing of SNF and blanket assemblies, for instance, a mixture of 50% of uranium and 50% of plutonium is separated;
– elimination of blankets in fast reactors of export designs for supplies to countries that do not possess nuclear weapons;
– establishment of international NFC centers.

Export supplies of fast-reactor NPPs require that spent FAs of the core and the irradiated blanket assemblies to be fully and unconditionally repatriated into the supplier country. This will require detailed monitoring of their irradiation in the reactor, continuous control of their presence in the cooling pool, and supervision as to the fuel repatriation into the supplier country or into international NFC centers.

On the one hand, the elimination of the blanket in a fast reactor makes impossible the production of plutonium with the isotope composition close to that in weapon-grade plutonium; on the other hand, it leads to a reduction in the breeding factor inside the fast reactor and, as a result, to the loss of additional plutonium that could be used for further uprating both fast and thermal reactors.

Startup of fast reactors on enriched uranium

In an open nuclear fuel cycle, as earlier noted, the greatest risk of proliferation comes from the fuel enrichment technology and long-term storage of SNF. In a closed nuclear fuel cycle, the greatest risk of proliferation is involved in the separated plutonium interim storage, fresh plutonium fuel fabrication and onsite fresh FA transportation stages. This risk is much lower when a technology with no pure plutonium separation is used in the SNF processing. A limited time of the spent FA intermediate storage and of the presence of plutonium-containing materials in all processing stages poses the smallest possible risk. And, as has already been noted, timely processing of SNF in the NFC excludes the risk of long-term SNF storage.

In Russia, at the present time, an option is investigated for fast reactors to be started on enriched uranium with a gradual conversion to mixed uranium-plutonium fuel using in-house plutonium. This option enables fast reactors to be independent of the presence of thermal reactor plutonium and excludes potential commissioning problems caused by limited quantities of plutonium-based fuel.

When fast reactors are started on uranium fuel and are further converted to mixed uranium–plutonium fuel, both sensitive technologies will be used: uranium enrichment and processing of spent fuel. In this case, plutonium with a small content of higher isotopes will be formed in much greater quantities not only in the blanket but also in the reactor core.

Table 2 presents isotope compositions of plutonium generated in uranium fuel of the BN and BREST fast reactor cores. These compositions have been obtained based on estimates from preliminary calculations [8,9].

As can be seen from the table, the content of plutonium-239 and higher isotopes is rather close to that of weapon-grade plutonium, excluding plutonium-238 the content of which is about 10 times and about 40 times as great as that of weapon-grade plutonium for the BREST reactor and the BN reactor respectively.

Plutonium-238 is the major contributor to the heat release in plutonium. A detailed analysis into the temperatures for different models of nuclear explosives using energy-grade plutonium

Table 2
Isotope composition of plutonium in spent uranium fuel of fast reactors.

Reactor type	Fuel burn-up	Isotope composition of plutonium, %				
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Weapon-grade Pu [6]	-	0.012	93.8	5.8	0.35	0.022
BN-1200 with UO_2	Life 5 years	0.4	91.8	7.7	0.3	0.02
BREST-1200 with UN	Life 5 years	0.1	95.5	4.3	0.1	0.003

Table 3
Options with different plutonium-238 contents analyzed by Kessler.

	Option 1	Option 2	Option 3	Option 4
Content of Pu in energy-grade plutonium, %	1.8	3.6	7	6.2
Heat release in nuclear charge, kW	0.12	0.24	0.46	0.40

was conducted by H. Kessler, a well-known German scientist. The results of his latest investigations are presented in a monography published in 2011 [10].

Prof. Kessler has developed, using only open information sources, a detailed design of a nuclear explosive and has analyzed the mechanism of the heat transmission from the plutonium contained in the nuclear explosive to the explosive lenses with respect to four application options for energy-grade plutonium with different contents of plutonium-238 (Table 3).

The first of the options suggests that baratol or "composition B", employed in the early nuclear weapons, should be used as the chemical explosive in explosive lenses. These explosive types have a comparatively low melting point (no more than ~80 °C), the achievement of which leads to the explosive lenses to be structurally broken.

The second options suggests the use of an advanced chemical explosive with higher heat conduction and melting temperature values which is capable to withstand high temperatures without losing its properties. Such explosives as DATB, HMX, PBX 9011, PBX 9404, PBX 9407 andPBX, remain serviceable at a temperature of up to ~190 °C, and, some of them, at up to ~250 °Cor even at a higher temperature.

A conclusion is made as the result of studies using up-to-date precision codes that the cooling of such devices (options 1 and 2) does not require any special measures and will be achieved naturally, thanks to thermal radiation and air convection. The chemical explosive used in these devices retains its properties.

Option 3 suggests that the item can be maintained serviceable thanks to the nuclear charge being forcedly cooled by liquid helium.

Option 4 also suggests that the serviceability of an item may be preserved by equipping all explosive lenses with rods manufactured of a highly heat-conductive material [7].

The key conclusion made by Prof. Kessler as the results of the studies is that plutonium with the content of plutonium-238 exceeding the above values may be considered self-protected in terms of proliferation. Therefore, when obsolete chemical explosives are used in nuclear explosive devices, it may be suggested that the content of plutonium-238 in the plutonium charge may be up to 1.8% without any forced cooling devices. When up-to-date explosive substances are used, the content of plutonium-238 in the plutonium charge may reach 3.6% also with no forced cooling measures taken. It should be noted that approximately such concentrations of plutonium-238 are achieved in the uranium SNF of light-water reactors when the fuel burnup reaches 33 and 60 GW•day/t.

Therefore, an increased content of plutonium-238 in spent fuel of fast reactors started on uranium cannot be looked upon as a technological barrier when such plutonium is used in nuclear weapons.

Uranium enrichment and nuclear nonproliferation problem

In connection with the development of the option suggesting the fast reactor startup on uranium fuel, the nuclear nonproliferation problem was studied as the result of which the following main conclusion has been made: the proliferator state, having obtained the enrichment technology by any way, will try to materialize its intent of coming into the possessing of nuclear weapons through the production of uranium with a sufficiently high enrichment, since the following is required:

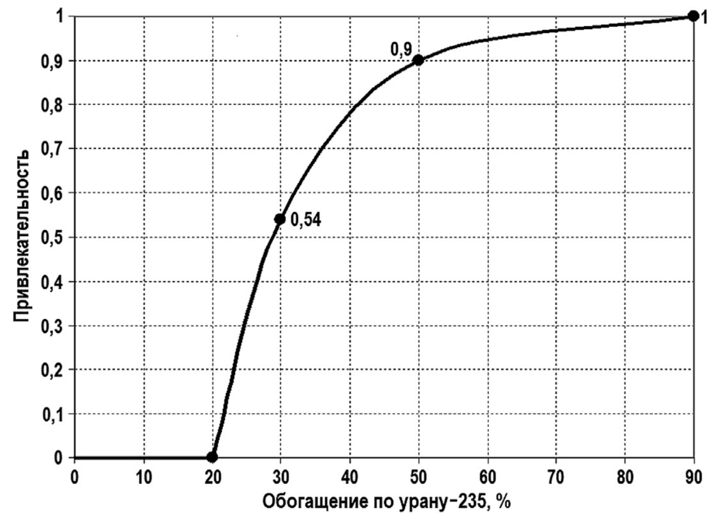
– a comparably small amount of fissile material, which leads to a "faster" device and, as a rule, to a large energy yield during an explosion;
– a smaller amount of initial material (natural uranium);
– a smaller amount of separation work (SWU);
– a shorter time.

To assess the suitability of fissile material for the manufacturing of nuclear weapons or a primitive NED, the notion or the factor of material *attractiveness* is introduced. This notion is an important part of the existing technologies used to assess the resistance of the commercial NPP NFCs to diversion or theft of nuclear materials [11]. The enriched uranium attractiveness function looks as follows

$$A(x) = mod[1.8 \cdot (2x - 1) \cdot 1n[x/(1 - x)] - 0.90].$$

By substituting the uranium enrichment value x, we will get the respective attractiveness values. Fig. 1 presents a diagram of the function $A(x)$.

And where fuel of nuclear reactors is used as the initial material instead of natural uranium, HEU will be produced with smaller quantities of the initial material and SWU and for a shorter time.



Привлекательность = Attractiveness
Обогащение по урану-235, % = Uranium0235 enrichment, %

Fig. 1. Enriched uranium attractiveness function.

Table 4
Initial material and SWU quantities for HEU production.

	Initial material for HEU production			
	Natural uranium	Thermal reactor uranium fuel	Fast reactor uranium fuel	
	0.711% of uranium-235	4% of uranium-235	15% of uranium 235	20% of uranium-235
Initial material mass	4.4 t	590 kg	150 kg	10 kg
SWU quantity	5.7×10^3	1.8×10^3	750	500

Table 4 presents selected comparative estimates for the production of 25 kg of uranium with an enrichment of 90%, if fresh uranium-based fuel of thermal reactors or fast reactors is used as the initial material. These estimates assume 0.2% of uranium-235 in the enrichment facility dumps.

It can be seen that the use of nuclear reactor fuel as the initial material for the HEU production leads to a greatly decreased demand for the initial material and SWU, which is expressed in a major reduction in the production time. When fuel of nuclear power reactors is used, two or one FAs will be essentially enough to have the initial material for producing HEU in one notable quantity (the approximate quantity of nuclear material, for which the potentiality of the nuclear explosive manufacturing cannot be excluded with the ureanium-235 enrichment exceeding or being equal to 20%, is 25 kg of uranium-235 [12]).

Since the potential proliferator is not expected to be saving much when producing HEU, it may afford a greater content of uranium-235 in the enrichment tailings, this leads to a smaller demand for SWU, and, therefore, reduces the HEU production time, but, on the other hand, requires more initial material.

It may be therefore suggested that supplies of enriched nuclear fuel to other countries involve a potential risk of this fuel to beg used as the initial material for obtaining high-enriched material.

Conclusion

Fast reactors started and operating on mixed uranium-plutonium fuel do not require a uranium enrichment technology. There is no long-term storage of SNF in a closed fuel cycle.

It is high time that fast reactors to be relieved of an unfair label as the most dangerous facilities in terms of the nonproliferation problem. Until now, all weapon-grade plutonium was produced globally in thermal reactors, and there is no reliable information that any notable quantity of it was produced in fast reactors.

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